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Measurement of Azimuthal Anisotropy at RHIC-PHENIX

Maya Shimomura[1,a] for the PHENIX Collaboration

[1] *Nara Women's University, Ktauoya Nishimachi, Nara, 630-8263, Japan*

Abstract. The transverse momentum (p_T) and centrality dependence of the azimuthal anisotropy of second harmonics(v_2) are measured for charged hadron species at various collision systems and energies such as $\sqrt{s_{NN}}$ = 62.4 and 200 GeV in Cu + Cu and Au + Au collisions and at $\sqrt{s_{NN}}$ = 200 GeV in Cu + Au collisions by the PHENIX experiment at RHIC. The higher order anisotropy (v_3) are also measured for charged hadron at $\sqrt{s_{NN}}$ = 200 GeV in Cu + Cu, Au + Au and Au + Cu collisions. From these systematic study, we found that the all results are consistent with eccentricity scaling, quark number + KE_T scaling and $N_{part}^{1/3}$) scaling except at small N_{part} in Cu + Cu at 62.4 GeV. Taking these scaling (quark number, KE_T, eccentricity and $N_{part}^{1/3}$) into account, there is a universal scaling for π/K/p v_2 with different energies, collision sizes and particle species.

1 Introduction

Relativistic heavy ion collisions have been considered as a unique way to create and study the quark-gluon plasma (QGP), where the quarks and gluons are de-confined. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was constructed to create and study the QGP. Azimuthal anisotropy of produced particles in relativistic heavy ion collisions is a powerful probe for investigating the characteristics of the QGP. Especially the strength of the elliptic anisotropy (v_2), which is defined by the second harmonics of Fourier expansion for the azimuthal distribution of the produced particles with respect to the reaction plane, is expected to be sensitive to the early stage of heavy ion collisions. At non-central collision, the overlap region is geometrically anisotropic, like an almond shape. When the produced matter has small mean free path, interacting each other enough to reach local thermalization, it creates pressure gradient. The geometrical anisotropy transfers to the anisotropy in the momentum phase space as flow because of this pressure gradient, and v_2 indicates the strength of this elliptic flow. Thus, the measured v_2 reflects the equation of state of the dense matter such as QGP, produced in the collisions. Recently the measurement of the triangle anisotropy (v_3) has also drawn scientific attention because most of it are expected to be created by the participant fluctuations in Au + Au and the estimation of the strength of the participant fluctuations strongly depends on theoretical models at initial conditions. Therefore, v_3 is expected to be able to put some restriction on initial condition models [3]. On the other hand, as same as v_2, v_3 should also develop with the pressure gradient at QGP. The important thing here is since the produced particles randomly emit before thermalization, the geometrical anisotropy decreases with time. Therefore, to let the geometrical anisotropy make elliptic and triangular flow, the thermalization should be occurred very early stage before the geometrical anisotropy is totally gone.

[a] e-mail: mayap@bnl.gov

2 Motivation

One of the most remarkable findings at RHIC is that the strength of v_2 can be described well by hydro-dynamical models in the low transverse momentum region (~ 1 GeV/c) [1]. In the intermediate transverse momentum region (1 ~ 4 GeV/c), v_2 is consistent with n_q and KE_T (= m_T - m_0) scaling, and the result supports a quark-recombination model [2]. The matter produced in the high energy heavy ion collision is expected to undergo several stages from the initial hard scattering to the final hadron emission. When the matter reaches thermalization and QGP is created, we expect hydro-dynamical behavior at quark level. Because experimentally we cannot see the QGP directly, we need a comprehensive understanding from thermalization through hadronization to freeze-out. The elliptic flow is expected to be created at QGP stage by pressure gradient, but it is important to note whenever the matter interacts with each other, there is a possibility to change v_2. [4]

For a more comprehensive understanding of azimuthal anisotropy, we have carried out systematic measurements of v_2, by measuring v_2 for identified charged hadrons in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}}$ = 200 and in Au + Au at $\sqrt{s_{NN}}$ = 62.4 GeV and also for inclusive charged hadrons in Au + Au and Cu + Cu at $\sqrt{s_{NN}}$ = 200 and 62.4 GeV. We have studied the dependence on collision energy, size and species of the produced particles comparing the $\sqrt{s_{NN}}$ = 2.76 TeV data from LHC. [9] Moreover, we measured v_2 for inclusive and identified charged hadrons in Cu + Au and v_3 for inclusive charged hadrons in Au + Au and Cu + Au at $\sqrt{s_{NN}}$ = 200. To study the detailed behavior of flow measurement, we examine the scalings to these results. We had expected that v_3 at Cu + Au is larger than that at Au + Au because Cu + Au collision provides additional triangular anisotropy at collision geometry while v_3 in Au + Au comes from initial fractuations.

3 Results

In Au+Au collisions, the values of v_2 as a function of p_T agree well at $\sqrt{s_{NN}}$ = 39, 62.4 and 200 GeV for measured centralities, 10-20, 20-30, 30-40 and 40-50%. However, the v_2 at 7.7 GeV is much lower than these. This results may indicate the energy between 7.7 and 39 is the region which switch from partonic flow to hadronic flow. We also compared the results of $\sqrt{s_{NN}}$ = 2.76 TeV data in Pb+Pb at LHC-ALICE, and it was found that v_2 at 2.76 TeV is very similar to the v_2 at 200 GeV especially at low p_T. [9]

Next, we compared different system size of collisions such as Au + Au, Cu + Cu, Pb + Pb and Cu + Au at $\sqrt{s_{NN}}$ = 200 GeV, 62.4 GeV and 2.76 TeV as a function of N_{part}. The values of v_2 agree well at $\sqrt{s_{NN}}$ = 200 GeV, 62.4 GeV and 2.76 TeV in Au + Au, but have clear differences between Cu + Cu and Au + Au, and Cu + Au results are between Cu + Cu and Au + Au. This is natural because the different nucleus collisions such as Cu + Cu, Au + Au and Cu + Au have different initial geometrical eccentricities at the same N_{part}. [10, 11] Normalizing v_2 by eccentricity, ε, (eccentricity scaling), all results follow one curve therefore, v_2 is scaled by the eccentricity at the same N_{part}. Here, we use the participant eccentricity, which includes the effect of participant fluctuations [5]. The values of v_2/ε are not a constant, therefore, v_2 can be normalized by ε at the same N_{part}, but N_{part} dependence still remains. Looking close to this dependence we empirically found that v_2/ε is proportional to $N_{part}^{1/3}$. This $N_{part}^{1/3}$ works in Au + Au, Cu + Cu collisions[10] and in Pb + Pb[9] and in Cu + Au [11] as shown in Figure 1 . Including results of $\sqrt{s_{NN}}$ = 2.76 TeV, $v_2/(\varepsilon \cdot N_{part}^{1/3})$ is independent of the collision systems except for small N_{part} in Cu+Cu at $\sqrt{s_{NN}}$ = 62.4 GeV.

One of the most famous results on RHIC v_2 measurement is that the v_2 for quark number(n_q) + KE_T scaling in Au+Au at at $\sqrt{s_{NN}}$ = 200 GeV.[2] The n_q scaling is consistent to the recombination model which assumes the quark level flow at QGP phase, and the KE_T scaling has been considered to be able

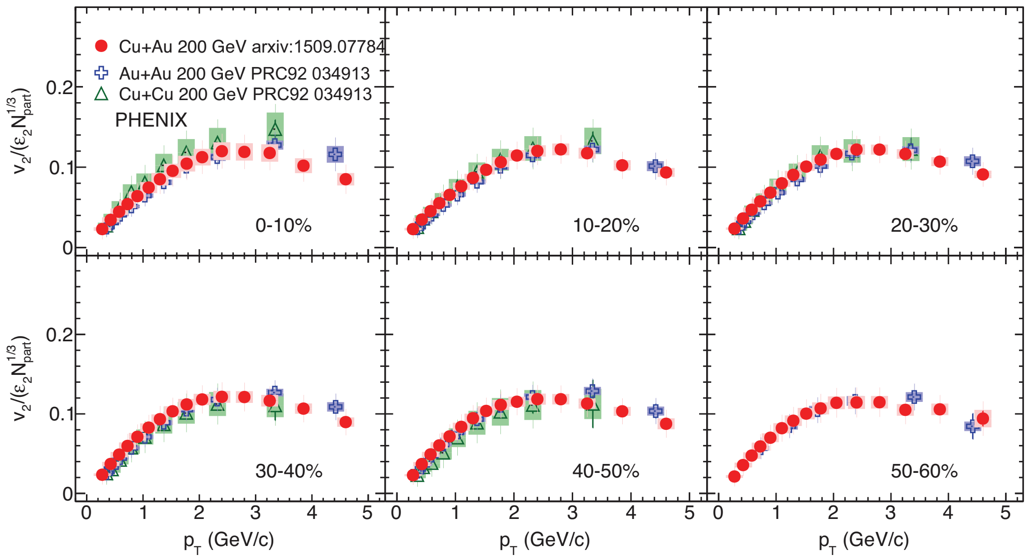

Figure 1. $v_2/(\varepsilon \cdot N_{part}^{1/3})$ vs. p_T for charged hadron in Au+Au, Cu+Cu and Cu+Au at $\sqrt{s_{NN}}$ = 200 GeV at indicated centrality bin in each panel. [9, 11, 12]

to subtract the difference of different particle v_2 at low p_T which is caused due to the radial flow effect. In Au+Au 200GeV collisions at PHENIX experiment, the large statistics and new detector allowed us to see that the both n_q and KE_T scaling works very well on various particle species including ϕ, Λ and deuteron, and even to see the break point of this scaling at KE_T = 1 GeV as shown in [8] . Above this p_T region, one can expect other mechanism is dominant to create v_2. For the systematic study, we also measured particle identified v_2 in Au+Au at $\sqrt{s_{NN}}$ = 62.4 GeV and in Cu+Cu and at $\sqrt{s_{NN}}$ = 200 GeV. It is found that v_2 in Au+Au at 62.4 GeV is also consistent with n_q + KE_T scaling. Moreover,the n_q + KE_T scaling mostly works out in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV for central collisions. There are the small discrepancy from the KE_T scaling at peripheral collisions at low p_T and the discrepancy from the KE_T scaling depends on N_{part}. The detailed quantitative comparison are written in [10]. Comparing between π and proton, the results indicate the larger N_{part} produces more shift for proton to higher p_T based on π. This N_{part} dependence of KE_T scaling behavior for the v_2 is explained by the radial flow effect with blast wave model in [8]. Additionally, KE_T scaling does not work out at $\sqrt{s_{NN}}$ = 2.76 TeV. Proton v_2 is shifted to higher p_T compared with π more than RHIC results.[9] We also measured particle identified v_2 for π/K/p in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV. Mass ordering can be seen at low p_T and baryon and meson splitting are also observed at mid p_T which seems to be consistent to n_q scaling.[12]

In addition to the fact that $v_2(p_T)$ is consistent at $\sqrt{s_{NN}}$ = 39 - 200 GeV, v_2 normalized by n_q + KE_T, eccentricity, and $N_{part}^{1/3}$ scaling follows a universal curve as shown in the right panel of Figure 2. This figure includes the 45 curves for π/K/p in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV, in Au+Au at $\sqrt{s_{NN}}$ = 62.4 GeV and in Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV for the five centrality bins from 0 - 50% in 10% steps. The combined data is fit with a single 3rd-order-polynomial, producing a χ^2/NDF = 1034/490 = 2.11 (including both statistical and systematic uncertainties). [10] This is a universal scaling for

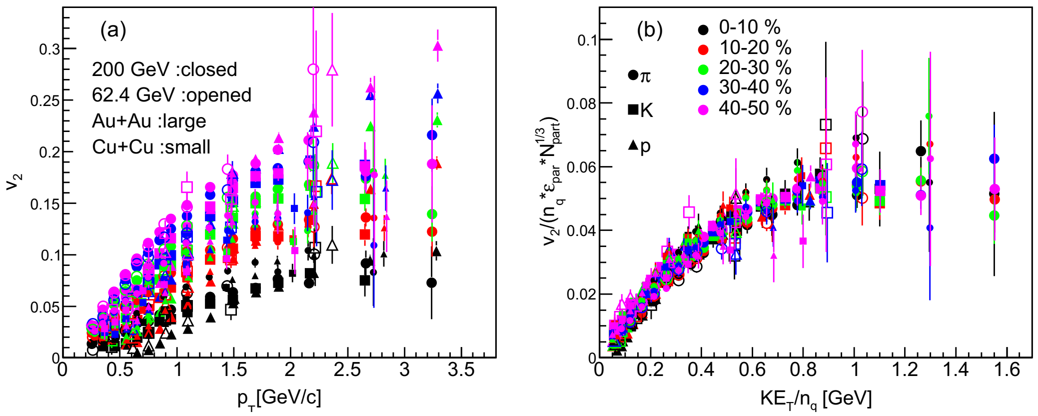

Figure 2. The left panel shows v_2 vs. p_T and the right panel shows $v_2/(\varepsilon \cdot N_{\text{part}}^{1/3} \cdot n_q)$ vs. KE_T/n_q for π/K/p in Au+Au at 200 GeV, in Au+Au at 62.4 GeV and in Cu+Cu at 200 GeV for five centrality bins over 0- 50 % in 10 % steps for each system.There are 45 data sets in each panel. [10]

v_2 with different energies, collision sizes and particle species, and it indicates that v_2 is determined not only by the geometrical eccentricity but also by the size of collision. This scaling assume that differential v_2 is consistent above 39 GeV while "v_2/ε vs. (1/S)(dN/dy)" scaling plotted in [7] assumes that the higher collision energy produces higher v_2. Therefore, this $N_{\text{part}}^{1/3}$ scaling works better for the differential v_2 at PHENIX results. The size dependence of v_2 can be understood as thermal freeze-out nature of produced particles based on hydrodynamical behavior, which is different from that of chemical freeze-out. [8] Moreover, this $v_n/(\varepsilon_n \cdot N_{\text{part}}^{1/3} \cdot n_q)$ scaling is consistent with v_3 results in Au + Au and Cu + Au for inclusive charged hadrons.

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